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UAS C2 Radio System – Final Phase 1 Development and Testing

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SUMMARY

Phase 1 of the Command and Control Communications (C2) Subproject of NASA's UAS Integration in the National Airspace System Project included the development and testing of prototype C2 radio systems. This information paper provides an overview of the functionality and testing of the fifth and final Phase 1 generation of the prototype radio system.

1. INTRODUCTION

1.1 NASA's UAS in the NAS Project's C2 Subproject Phase 1 (2012-2016) emphasized LOS C2 terrestrial communications and the development of technical data for supporting the completion of C2 Terrestrial Minimum Operational Performance Standards (MOPS) by RTCA Special Committee 228 (SC-228). A significant element of Phase 1 consisted of the development and testing of prototype C2 terrestrial radio line-of-sight (LOS) radios. Previous contributions have described the C2 terrestrial radio technology assessments and waveform studies (ACP-WG-F/26 WP07, ACP-WG-F/27 WP20 and WP21); development and design aspects of the prototype radio was described (ACP-WG-F/29 IP04); flight tests of the first generation prototype C2 radio (ACP-WG-F/29 IP06); flight tests of the second generation prototype C2 radio operating in C-Band (ACP-WG-F/30 IP09); and ground station handoff testing of the second generation radio at L-Band (ACP-WG-F/32 IP03).

1.2 Three additional generations of the prototype C2 radio were developed during Phase 1. These additional generations provided multiple aircraft capability for the ground radio and adjusted data rates and waveforms to enable radio testing to provide test data supporting the completion of C2 Satellite Communications MOPS by RTCA SC-228. The 5th generation radio encompassed updates to data rates and

waveforms to align with final C2 MOPS and was used to perform C2 MOPS verification and validation tests. An extensive report on the test results is to be published soon as a NASA Technical Memorandum. The following sections provide a general description of the 5th generation radio functionality and an overview of the verification and validation tests.

2. C2 RADIO DESCRIPTION

2.1 The NASA Glenn Research Center entered into a cost-sharing cooperative agreement with Rockwell Collins, Inc., the NASA Glenn Research Center for the design of a prototype UA C2 (also referred to as Control and Non-Payload Communications, CNPC) radio system that will allow safe and efficient communications within the L-Band and C-Band spectrum allocations. The C2 radio development was accomplished through a series of four evolutionary upgrades to the initial C2 radio waveform and radio hardware. Table 1 describes the general technical progression of the radios, beginning from a point-to-point L-Band demonstration through dual-band radios offering multi-aircraft control and networked hand-off capability.

Table 1 – Evolution of Prototype UA C2 Radio

Generation 1:	L-Band only, single aircraft, single ground station, point-to-point C2
Generation 2:	Added C-Band, single aircraft, multiple ground stations (networked mode). In-flight “hand-offs” between ground stations
Generation 3:	Added capability for multiple aircraft
Generation 4:	Update of data rates to perform testing for preliminary C2 MOPS. Adjustable data rates
Generation 5:	Updates to data rates and waveforms to align with final C2 MOPS. Used to perform C2 MOPS verification and validation tests

2.2 Service Classes and Data Classes

2.2.1 RTCA SC-228 defined four service classes based on the type of UA communications traffic that would be required. The four service classes are shown in Table 2. For example, a small UA operating in a remote area at low altitude may only require uplink control and downlink telemetry services (Service Class 1), whereas a larger UA operating over a long range and high altitude would require all types of communications services (Service Class 4).

Table 2 – Types of Communications Traffic in UA Service Classes

	Telemetry	Voice	Navigational Aids	Aircraft Targets	Weather Radar
Service Class 1	✓				
Service Class 2	✓	✓			
Service Class 3	✓	✓	✓	✓	
Service Class 4	✓	✓	✓	✓	✓

2.2.2 NASA performed further analysis of the traffic types for each service class of UA to determine the minimum data rates required, including data requirements for the airfield departure, en-route, and airfield arrival phases of flight. The analysis included UA operations in both manual and automatic modes, in which the UA controls would be operated either by a ground-based pilot (manipulating control surfaces in near real time) or by adjusting flight waypoints in an auto-piloted UA. This analysis accounted for the raw payload data, overhead for transport and network layer headers and security, and for header compression. These data rates were then converted to user payload bytes per C2 frame assuming 20 Hz operation for the departure and arrival phases and 15 Hz operation for the en-route phase (5 Hz are reserved for the en-route acquisition of other ground stations to enable handoffs). The user payload sizes identified in the analysis were then verified using a combination of specialized testing using the Generation 4 radios and simulations. The results of the analysis indicated that a minimum of four data classes could efficiently support the four services during various phases of flight. The four data classes defined and implemented in the Generation 5 radio are shown in Table 3.

Table 3 – C2 Data Classes

	User Payload Bytes/Frame*
Data Class 1	44
Data Class 2	100
Data Class 3	160
Data Class 4	216

* Includes L2 header(s) but excludes bytes for acquisition, preamble, midambles, postamble, FEC, and CRC

2.3 Waveform Description

2.3.1 The basic structure of the Generation 5 prototype radio waveform has not changed substantially from the original Generation 1 radio. Each second of time is divided into twenty 50-ms frames in order to support a maximum message rate of 20 messages per second. Using Time Division Duplexing (TDD), each of these frames is further subdivided into an uplink subframe and a downlink subframe, as shown in Figure 1.

2.3.2 The Generation 5 waveform supports either point-to-point or networked modes of operation. In the point-to-point mode, a single ground station (GS) radio communicates to a single UA radio using up to all 20 frames. The networked mode of operation is designed to allow a set of GS radios (acting as one) to communicate to multiple UA radios using one of the networked uplink modes that use Time Division Multiple Access (TDMA) to divide the uplink subframe into slots that are assigned to individual UA. For the Generation 5 prototype system, one C2 radio can provide the uplink communications for up to 24 individual UA (m=24). In the downlink, multiple Frequency Division Multiple Access (FDMA) channels are used to support multiple UA.

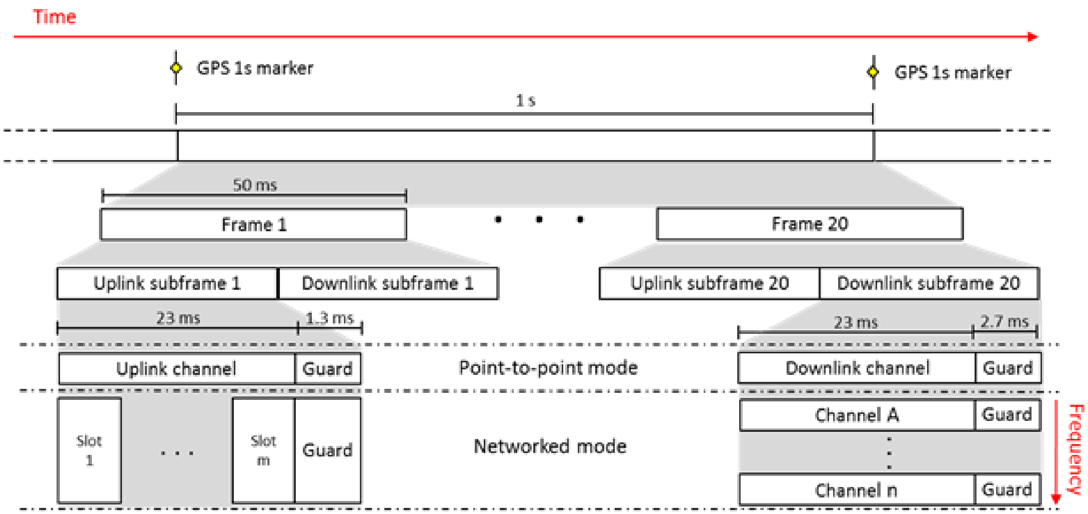


Figure 1. Waveform Overview

2.4 Waveform Modes

2.4.1 The Generation 5 prototype radio waveform supports the four data classes through different waveform modes as indicated in Table 4. For the downlink and point-to-point uplink, a separate waveform mode is defined for each data class. The networked uplink waveform modes are defined by the number of slots provided. The data rate and bandwidth are adjusted to provide the same number of bits per slot. For example, the 12-slot uplink has twice the bandwidth and data rate of the 6-slot uplink, but the total number of bits per slot remains the same. In the networked uplink, data classes are supported by allocating multiple slots, with data class 1 utilizing one slot and data class 3 utilizing 3 adjacent slots.

Table 4 – Generation 5 C2 Waveform Modes

	Waveform Mode*	Data Class	Slots	Bandwidth (kHz)	Physical Data Rate (kbps)
Downlink and Point-to-Point Uplink	A	1	-	30	34.5
	B	2	-	60	69
	C	3	-	90	103.5
	D	4	-	120	138
Networked Uplink	UL3	1-3	3	90	103.5
	UL6	1-3	6	180	207
	UL9	1-3	9	270	310.5
	UL12	1-3	12	360	414
	UL15	1-3	15	450	517.5
	UL18	1-3	18	540	621
	UL21	1-3	21	630	724.5
	UL24	2-3	24	720	828

*Only highlighted waveforms implemented in the prototype radio

2.4.2 Figure 2 shows a single frame of an example networked C2 system supporting 4 UA. The uplink is configured for the 360 kHz 12-slot mode while six downlink channels are allocated in the same spectrum. In this example, UA1 requires data class 1 for the uplink and downlink and is allocated one uplink slot and a 30 kHz downlink channel. UA2 uses two uplink slots and a 60 kHz downlink channel to support its requirement for data class 2 uplink and downlink. UA3 receives 3 uplink slots and transmits in a 90 kHz downlink channel for data class 3. UA4 requires a data class 3 uplink and data class 4 downlink, and as such is allocated 3 uplink slots and one 120 kHz downlink channel. Note that it is not a requirement for the uplink and downlink subframes to utilize the same spectrum. The downlink channels also need not use contiguous spectrum

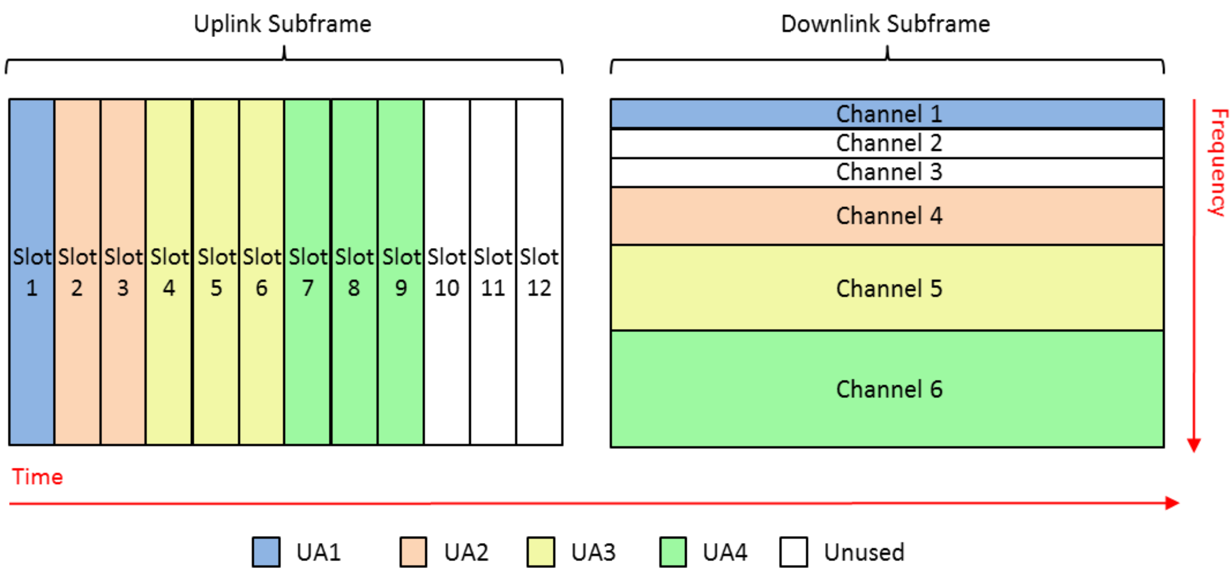


Figure 2. Example Networked C2 Frame Usage for 4 UA

2.4.3 All waveform modes are modulated using Gaussian Minimum Shift Keying (GMSK), which is a continuous phase modulation with constant power envelope. The waveforms can be configured to operate over a range of frequencies and output powers. The L-Band is configurable for frequencies between 961-974 MHz with output powers of approximately ¼ W to 6 W. The C-Band radio is capable of operating at the frequencies of 5031-5090 MHz at approximately ½ W to 25 W. The constant power envelope of GMSK modulation reduces the complexity of the radio transmitter amplifiers, but at 1 bit per symbol GMSK only offers bandwidth efficiency of 1.15 bits per hertz. Future radios would likely incorporate more efficient modulation techniques to conserve frequency spectrum while improving data throughput.

3. GENERATION 5 C2 RADIO TESTING

3.1 Test System Description

3.1.1 Descriptions of the test system can be found in ACP-WG-F/29 IP06, ACP-WG-F/30 IP09, and ACP-WG-F/32 IP03. The primary elements of the system are the test aircraft and GS, both of which are monitored and controlled by a centralized test operations center at NASA Glenn Research Center. One pair of

C2 radios (one L-Band and one C-Band) was installed in both the test aircraft and each ground station (GS) to establish bi-directional radio connectivity, allowing researchers to simultaneously monitor both air-to-ground and ground-to-air signal propagation characteristics in both frequency bands.

3.1.2 In order to capture data in several specific terrain settings, a GS was placed in one of three unique geographic locations and the planned aircraft flight pattern shifted accordingly to that location. For flight tests over hilly terrain, GS2 was installed at the Ohio University Gordon K. Bush Airport in Albany, Ohio (airport designation: KUNI). For flight tests over urban environments and capturing airfield departure and standard climb-out to class A airspace, GS1 at the GRC Lewis Field campus in Cleveland, Ohio was used. For the over-water tests, a mobile equipment trailer with extendable antenna mast (designated GS3) was temporarily positioned at the extreme western edge of Lake Erie in Sandusky, Ohio. Each GS was equipped with an Internet connection for remote control, monitoring, programming, and test operations. Figure 3 depicts the locations of the Albany and Cleveland GS locations and the corresponding flight test frequency authorization zones of operation.

Figure 3 - US Map Identifying Test Locations and 190 km-Radius Flight Zones

3.2 Flight Measurement Campaign

3.2.1 The validation flight tests were conducted during the three-month period from February to April 2016 in the airspace above Ohio and the adjoining Lake Erie area. The objective of the testing was to collect in-flight data measuring the operating range and data throughput capabilities of the C2 system. From this data, UAS designers and operators would be able to assess the capability of the C2 link to safely support the command and control, air traffic control/pilot communication, and detect-and-avoid functions needed for future UAS operation. Flight tests were flown at representative ranges and altitudes envisaged by RTCA SC-228 as being of interest and that would offer UAS operational utility.

3.2.2 For each test flight, the NASA research aircraft was piloted between pairs of preselected waypoints at fixed range from the ground station. Aircraft altitude, attitude, and airspeed were held nearly constant between waypoints to create a one-way flight "segment" of nominally 3.5-minute duration. The test aircraft flew the path between each pair of waypoints in two directions and at multiple altitudes to capture the

effects of terrain obstruction at multiple elevation angles, multipath reflections, and signal dispersion. Flight segments were flown at 35, 65, and 100 nmi range from the ground station to examine different received signal strengths. In addition to transverse flight paths, an inbound or outbound segment was flown at each test location. Test data from these flight paths often provided valuable information on multipath interference as well as maximum C2 radio range. A summary of flight altitudes, ranges, and flight paths is presented in Table 5.

Table 5 – Validation Flight Test Summary

Validation Flight Test Data Summary			
Waypoints: Range:	A-B 35 nmi	C-D 65 nmi	E-F 100 nmi
Hilly Terrain (L and C-Band)			
	14000 7500 3500	17500 14000 10000 6500	17500 15500 13500
	inbound descending		
Fresh Water (L and C-Band)			
	5000 3000 1500	10500 6500 3500	17000 11500 7000
	outbound		
Standard Departure (L and C-Band)			
	outbound run 1, ascending		
	outbound run 2, ascending		
Reduced-Power Flight Range Demonstration (L-Band only)			
	outbound run, 11600 ft altitude		
	inbound run, 11600 ft altitude		
	transverse segments at 20, 25, 30, 35, 40, 45, 50, and 56 nmi range and 11600 ft altitude		
Networking/Multi-User Test (L-Band only)			
	25 nmi radius orbit, 8500 ft altitude		

3.2.3 Figure 4 shows the flight track of the NASA aircraft for testing over hilly terrain in southern Ohio from a low-altitude perspective to show the flight path at various test altitudes. Waypoints are identified with alphabet characters A-E. The gold-colored trace describes the complete flight path of the aircraft, including all reversals, ascent/descent maneuvers, and range changes. The flight segments between waypoints are highlighted in yellow, which precisely represent the locations where RF data was captured for evaluation.

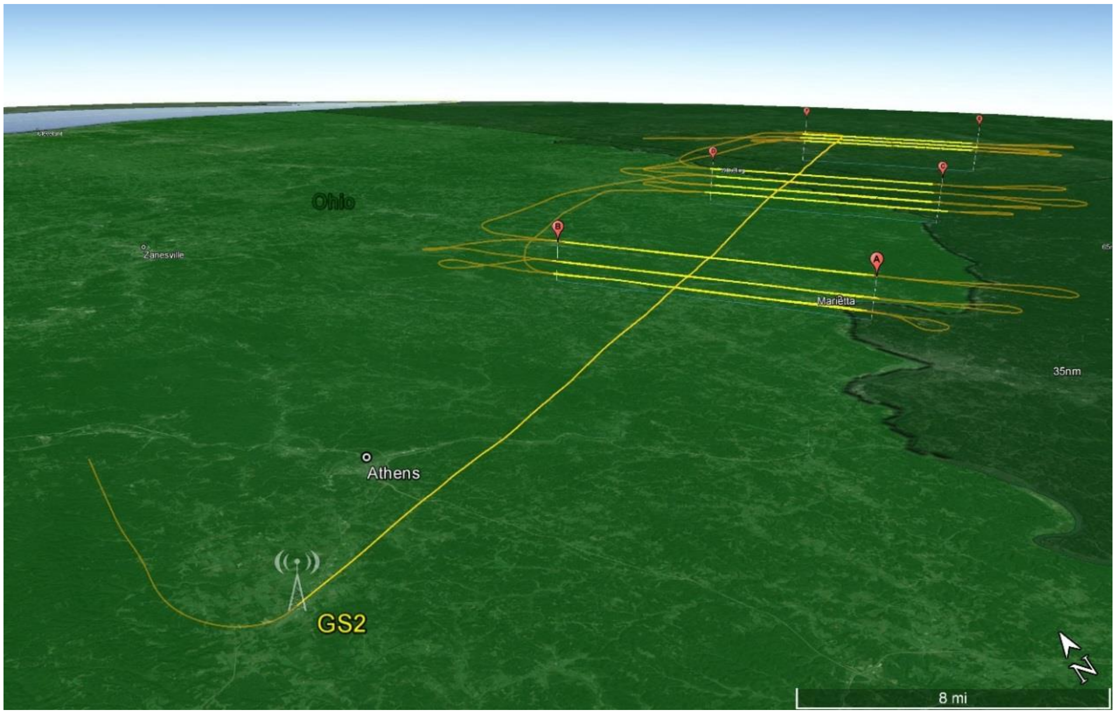
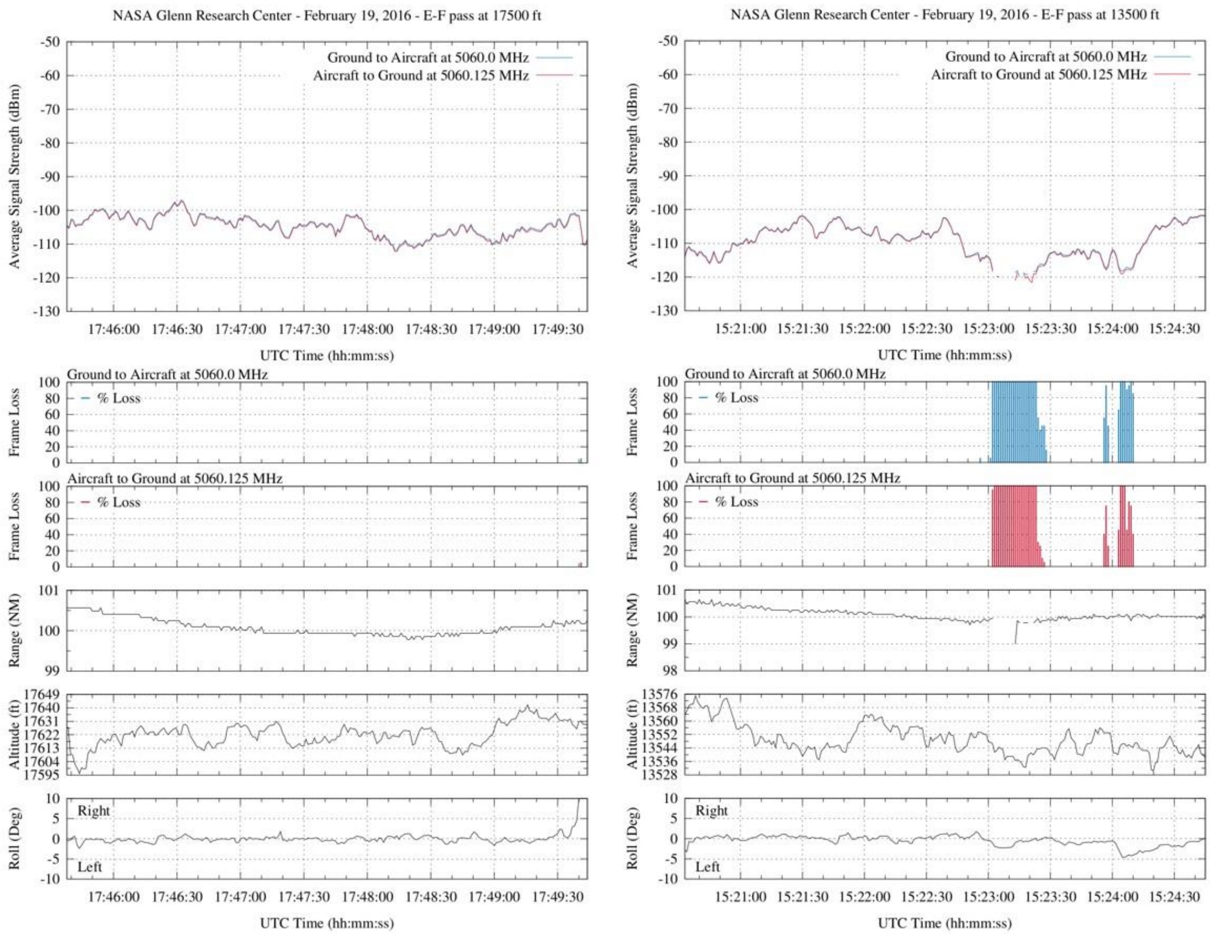


Figure 4 – Perspective View of Flight Path over Hilly Terrain Highlighting Data Capture Segments, February 19, 2016. Image ©2016 GoogleEarth

3.2.4 Figure 5 presents typical flight segment data using the C-Band CNPC radios. In both of these plots, the aircraft was traveling transverse to the radiation path at a distance 100 nmi downrange from GS2. In both plots, the aircraft was traveling in the same direction, moving from waypoint E to F, but at two different altitudes. Signal strength values measured at the radio receivers are plotted along the vertical axis for both the ground-to-air "uplink" (blue trace) and air-to-ground "downlink" path (red trace). The signal strength data is measured on each data frame at a rate of 20 times per second, then plotted as an average value every one second to time-correlate with aircraft flight parameters. All signal strength traces are for the point-to-point, 90 kHz wide data channel at the 103,500 bits/sec symbol rate (waveform C), as requested by RTCA SC-228. Both the uplink and downlink signal strength traces are plotted in each figure, shown in red and blue, and are nearly identical.

3.2.5 Directly below the signal strength traces are the percentages of data frame loss averaged over one second at the ground and aircraft receivers. Where the CNPC radio link was transferring all data without error, the data are presented as 0 percent frame loss and no trace is visible on the grid. Where errors occurred in the radio link, the lost frame data created a narrow, visible vertical line, or "impulse", ranging from 0 to 100 percent, where the latter represents a total loss of radio link. Aircraft parameters are plotted in the lowest portion of each figure.

3.2.6 The obvious difference between two plots in Figure 5 is the frame losses occurring at the 13,500 ft altitude, showing up as red and blue frame loss traces in Figure 5(b). These losses are caused by terrain obstructions (hills) that interrupt the line-of-sight path between the GS and aircraft antennas. Aircraft altitudes were intentionally selected to yield elevation angles of less than 2° above the horizon for the tests, which in this case caused these terrain-induced RF propagation issues.



(a) (b)

Figure 5 – C-Band Signal Strength and Frame Loss over Hilly Terrain at 100 nmi Range, at 17,500 ft (a) and 13,500 ft (b).

3.2.7 As shown in Table 5, testing was performed during two ATC-directed standard departures from Cleveland Hopkins International Airport and ascent/climb out to Class A airspace. Test results for C-Band indicate that the aircraft could ascend to a 20,000-foot cruising altitude with low frame losses before reaching a downrange distance of 50 nmi from the airfield. ATC-directed course changes result in aircraft roll which often disrupted the C2 signal, and multipath interference disrupted the CNPC link for brief periods. L-Band test results display many of the same properties.

3.2.8 To demonstrate the CNPC range at reduced transmitter power level, a separate flight test was performed. To execute this test, the output RF power level from both airborne and ground station L-Band radios were each reduced to deliver only 10mW of RF power at the antenna inputs. The aircraft was flown on outbound and inbound headings, then through a serpentine pattern, all over the same hilly terrain used in the validation testing at an altitude of 11,600 feet for all tests. At the reduced power level, maximum range was approximately 50 nmi. Outbound and inbound runs indicate the presence of a substantial multipath interference at a range of approximately 22-27 nmi downrange, believed to be caused by a ground reflection.

3.2.9 The final test to describe is the network multi-user test. This flight test was performed to test the transmission of user data over a multi-ground station network architecture. The primary metric of importance for these experiments was the total, one-way latency of the messages between the aircraft and the ground-based pilot. This latency includes not only the communication latency of the prototype radios but also the latency of the ground support network. A breakdown of the different latency factors is shown in Figure 6. In general, higher-priority C2 and voice data had nominally 50 – 100 ms of transit delay (latency) with very little latency jitter. In service class 4, the lower-priority, weather and target data messages incur the expected larger transit delays, but average latency still falls below 500 ms.

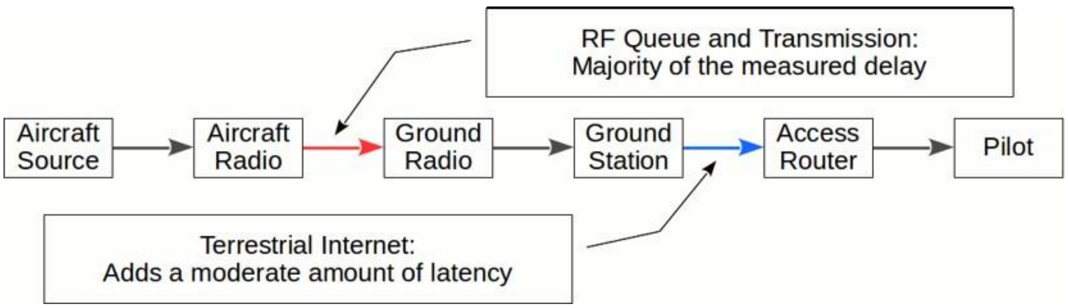


Figure 6 – Latency Factors

3.3 Overview of Test Results

3.3.1 The UAS in the NAS Project Generation 5 C2 Radio flight test campaign produced a significant amount of empirical data for validation of the C2 radios in relevant flight environments. The primary goals of demonstrating radio-to-radio connectivity, acquiring performance data for system analysis, and supplying the RTCA SC-228 working group with validation data were all achieved.

3.3.2 The NASA Technical Memorandum to be published soon detailing the flight test results provides a preliminary analysis of the flight test data and was intended to validate that radio electronics of this type could successfully communicate command and control information with an aircraft in flight. Efforts are underway to study the radio performance in greater detail and to refine the understanding of performance capabilities to assist in applying CNPC radios in future systems.

3.3.3 Terrain Obstructions and Multipath Interference

3.3.3.1 The diverse set of flight test environments offered in the Ohio test areas provided researchers excellent opportunities to investigate multiple radio frequency propagation characteristics. The relatively flat terrain in the northern Ohio flight test area, for example, afforded a significant unobstructed line-of-sight (LOS) distance to provide valuable data on the maximum RF range of the C2 radios. Similarly, the hilly terrain in the southern Ohio region allowed a thorough investigation of the LOS obstruction issues by flying the test aircraft at specific planned altitudes near known terrain features. Additionally, test flights over the open fresh water of Lake Erie provided excellent information on multipath interference and signal dispersion from the water surface. Evidence of multipath interference and terrain obstruction appears in many of the flight test data sets included in this report. Flight test data also indicates adverse effects of manmade structures on C2 signal propagation.

3.3.4 Data Latency

3.3.4.1 Testing has demonstrated that the message prioritization scheme designed into the CNPC prototype radios works well with IP network traffic classes. For the service class 2 and service class 4 cases, the prototype radios transferred the higher-priority C2 and voice data with nominally 50 – 100 ms of transit delay (latency) with very little latency jitter. In service class 4, the lower-priority, weather and target data messages incur the expected larger transit delays, but average latency still falls below 500 ms. Flight testing confirmed that header compression techniques utilized in the NASA system architecture worked effectively to reduce delays and keep latency variation low.

3.3.5 Communications Capability

3.3.5.1 The prototype radios used in this test campaign demonstrated reliable C-Band and L-Band connectivity at a range up to 100 nmi using only the internal transmitters. This operating range is well in excess of the 69 nmi target range established in early UAS architecture studies.

3.3.5.2 One of the primary goals of the CNPC flight test campaign was to validate the requirements of the RTCA C2 Terrestrial MOPS to prove that the prototype radios can support UA operation at the ranges and altitudes of interest to UAS designers and operators. The NASA in-flight test data shows that the prototype CNPC radios are capable of these operations, in either a point-to-point or multi-user network configuration. Furthermore, the flight tests demonstrated that UA can be provided with long-range, reliable RF channels and low user data error rates that can ultimately allow for safe and efficient UAS operation.

4. **CONCLUSION**

4.1 NASA’s UAS in the NAS Project’s C2 Subproject Phase 1 has been completed. A primary objective of Phase 1 was to develop and test prototype C2 radio systems, in conjunction with RTCA SC-228’s development of C2 Terrestrial MOPS. The development of the prototype radios progressed through five generations, adding capabilities and adjusting operational functionality as SC-228 refined requirements. Generation 5 of the C2 radio corresponded to the final MOPS drafts, and flight testing results of this final radio version provided validation data for completion of the MOPS.

4.2 In this information paper we provided a functional description of the Generation 5 prototype C2 radio, the validation flight test campaign, and some example results. The primary flight test campaign goals of demonstrating radio-to-radio connectivity, acquiring performance data for system analysis, and supplying the RTCA SC-228 working group with validation data were all achieved. Analysis of the flight test data continues and will be published in the future.

— END —